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The effect of welding speed and contact-tip-to-workpiece distance on the microstructural homogeneity and bead profile of tandem GMA steel welds

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Abstract

Automated tandem gas metal arc welding (T-GMAW) has been identified as a welding system potentially capable of increasing productivity and minimising distortion in the fabrication of ship panels. The T-GMAW process was used in pulse-pulse mode on 6 mm plain carbon steel plate to determine the effect of welding travel speed (WTS) (1.0–2.0 m/min) and contact-tip-to-workpiece distance (CTWD) (20–35 mm) on weld metal microstructure and bead profile. In this mode, the leading and trailing welding wires alternately transfer metal into a single molten weld pool at welding travel speeds much greater than those used in conventional single-wire gas metal arc welding (GMAW). The results show that for the bead-on-plate (BOP) welding of 6 mm plain carbon steel plate, adequate weld pool mixing and an acceptable level of microstructural homogeneity in the solidified weld metal were achieved for all welding conditions. BOP welding tests were also undertaken on 20 mm plain carbon steel plate which results in a greater weld cooling rate compared with the thin 6 mm plate. In the 20 mm plate, a relatively homogenous weld metal microstructure was also present, but there was evidence of limited weld pool mixing. Also, in-situ analysis of the arcs during welding and post test characterisation of the BOP samples showed that arc stability and bead profile are sensitive to both CTWD and WTS.

1. Introduction

Modernisation of the processes used in the fabrication of steel naval surface vessels in Australia is required in order for its shipbuilding industry to remain globally competitive and deliver cost savings to Defence. The hull, shear strakes and superstructure of naval surface vessels are weld fabricated using a modular construction technique. The modules, which are also joined by welding upon completion, usually have different geometries. Consequently, the fabrication of naval vessels is not suited to full-scale automation, but there is scope for significantly improving productivity by selectively targeting specific areas of the fabrication process for localised automation and/or mechanisation.

The concept of mechanisation and selective automation in international shipbuilding is not new. In Japan, shipbuilding yards incorporated large gravity fed electrodes into the manual metal arc welding process shortly after they were developed in 1940, only twenty years after the first all-welded (non-riveted) ship [1]. Furthermore, submerged arc welding (SAW), which is considered a semi-automated process, is used in combination with gas metal arc welding (GMAW) processes. However, SAW can not be undertaken out-of-position, and the use of flux slows down production due to the extra time required for setup and slag removal.

Automated tandem gas metal arc welding (T-GMAW) processes, which are commercially available but not yet optimised for implementation into naval ship construction, have been identified as potential replacements to conventional welding processes. These types of processes are being evaluated for the weld fabrication of naval surface ship hulls made from conventional and high strength steels such as HSLA65. Their appeal stems from an ability to (i) deliver high deposition rates (comparable to SAW), (ii) perform out-of-position welding, and (iii) achieve lower levels of weldment distortion. High-performance welding is reported to commence at deposition rates of 8 kg/hour [2]. The use of T-GMAW processes allows deposition rates much greater than 8 kg/hour to be achieved. End-users can convert these deposition rates into welds with fewer beads (i.e. larger seam cross-sections [3]) or increased welding travel speeds. The latter is the likely approach to be beneficial to naval shipbuilding so as to ensure naval hull weldments with adequate toughness, strength and less distortion.

The work presented here was undertaken on T-GMAW in the pulse-pulse mode. In this mode, the wires (electrodes) are fed from separate wire feed units through to two contact tubes, which are electrically isolated inside a single torch head [4]. The power sources for both wires (electrodes) are synchronised, thus enabling metal from each wire to be alternately transferred into a single weld pool [4]. The welding parameters can therefore be independently set for each wire to achieve the desired welding performance. This process has been used extensively for the welding of aluminium and it has been a key process in the weld fabrication of aluminium spherical-tank LNG carriers, which requires high-quality welds out-of-position [5]. Nonetheless, the use of pulsed T-GMAW in naval steel/aluminium shipbuilding has been limited. Two processes not investigated in the current work include (i) non-synchronised T-GMAW with 15-20 mm electrode spacing, and (ii) twin-wire welding in which the two wires are fed through a single contact tube [3, 6]. These two processes have not been considered for this study since their control of arc energy heat input is considered inferior to the pulsed T-GMAW process selected for this study.

This paper reports on the preliminary findings from a larger project that aims to gain a detailed understanding of the effect of weld process variables on T-GMAW weldments with the ultimate aims of improving the structural integrity of weldments, minimising hull distortion and improving productivity to deliver improved operational capability and cost-savings to Australian Defence. Specifically, the effect of contact-tip-to-workpiece distance (CTWD) and welding travel speed (WTS) on weld-bead microstructure and weld-bead profile of tandem gas-metal-arc (GMA) steel welds are discussed in the current work. Additionally, potentially important considerations for pulsed T-GMAW on steel plates of high thickness (e.g. 20 mm) are presented.

2. Experimental Procedure

Bead-on-plate (BOP) welds were deposited onto plain carbon steel (6 mm or 20 mm in thickness) using pulsed T-GMAW to determine the effect of CTWD and WTS on (i) process stability, (ii) weld metal microstructure and (iii) bead profile. For each test, a 200 mm weld bead was deposited onto the centre of a plain carbon steel plate (300 mm long x 150 mm wide). The oxide layer on the steel plate was removed by surface grinding and the plate was clamped down prior to welding.

ER70S-6 wire (1.2 mm in diameter) and a shielding gas containing 16% CO_2, 2.75% O_2 and 81.25% Ar were used for all welds. The ER70S-6 wire was selected as it conforms to Lloyd's Register rules [7] for the welding of 360 MPa steels (e.g., DH36—shipping grade steel), and it also meets the mechanical property requirements for 450 MPa (e.g. HSLA65—candidate surface ship steel) steels. The shielding gas composition was chosen for its optimum balance between spatter, penetration and bead shape. The nominal chemical compositions of both the base plate and wire are shown in Table 1.

Table 1: Nominal chemical composition (wt %) of the plain carbon steel plate and the ER70S-6 welding wire. Balance is predominantly Fe.

	C	Mn	Si	S	P
Base plate	0.22	1.6	0.55	N/A	N/A
ER70S0-6	0.07	1.55	0.88	0.012	00.015

A single torch head attached to two Fronius Trans Synergic 4000 power supply and wire feed systems was used (Figure 1(a)). The two welders are synchronised to time-co-ordinate the metal transfer from the electrode to the molten weld pool, and the welding parameters for each unit can be individually adjusted because each wire has its own externally insulated contact tip within a single torch head (Figure 1(b)). A high speed welding tractor was used to reach the required travel speeds. Table 2 shows the fixed welding parameters that were used in the experimental test plan, which is outlined in Table 3. Test plates were photographed in the as-welded condition to show whether the weld bead from the trailing wire could be distinguished from the weld bead of the leading wire. A cross-section of the weld was then taken from the centre of the plate and metallographically prepared for optical microscopy in order to assess the bead profile (shape and depth of penetration) and weld metal microstructure.

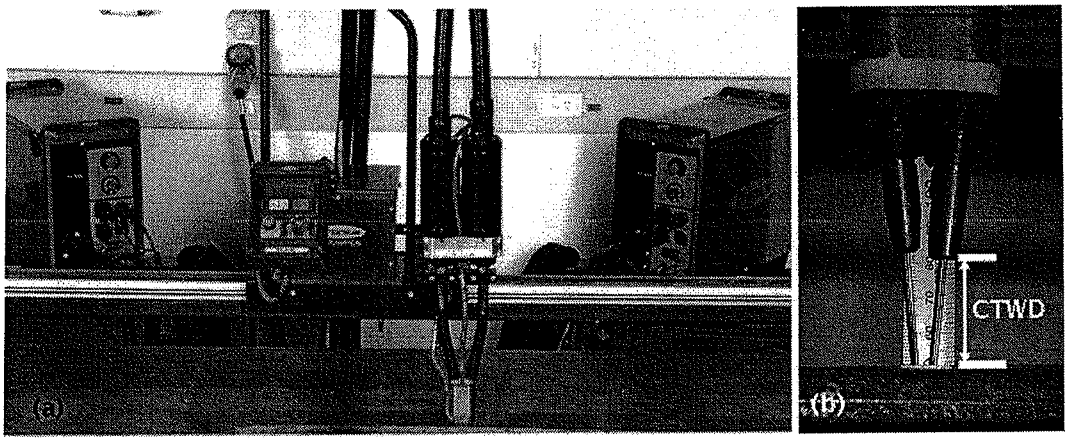

Figure 1: (a) Photograph of the welding setup used for the experimental program, and (b) photograph of the torch head geometry (setup at an average CTWD of ~30 mm).

Table 2: Fixed welding parameters for the experimental program listed in Table 3.

	Preheat temp. (°C)	**Welding Mode**	**Polarity**	**Arc Length Factor (%)**	**Torch Angle (°)**	**Gas Flow Rate (l/min)**
System	20	Pulse/Pulse	N/A	N/A	N/A	24
Lead	N/A	N/A	DC+	0	90	12
Trail	N/A	N/A	DC+	0	80	12

Table 3: Experimental test plan including the variable test parameters.

Test No.	**Plate thickness (mm)**	**CTWD (mm)**	**WTS (m/min)**	**WFR_{LEAD} (m/min)**	**WFR_{TRAIL} (m/min)**	**Deposition Rate (kg/hour)**
1	6	20	1.0	14	14	14.4
2	6	25	1.0	14	14	14.4
3	6	30	1.0	14	14	14.4
4	6	35	1.0	14	14	14.4
5	6	20	1.5	14	14	14.4
6	6	25	1.5	14	14	14.4
7	6	30	1.5	14	14	14.4
8	6	35	1.5	14	14	14.4
9	6	25	1.6	14	14	14.4
10	6	25	2.0	14	14	14.4
11	20	25	1.0	14	14	14.4
12	20	20	1.0	12	10	11.3
13	6	20	1.0	12	10	11.3

3. Experimental Results

Figure 2(a-h) shows photographs of the cross-sections of the welding BOP experiments on 6 mm plain carbon steel plate conducted at welding travel speeds of 1.0 and 1.5 m/min, and CTWD's of 20, 25, 30 and 35 mm. These photographs illustrate the size and shape of the weld bead, depth of penetration and the extent of undercut for the welding parameters used (Tables 2 and 3). The weld beads produced at a WTS of 1.5 m/min (Figure 2(e-h)) were considered more appropriate for multiple-run welds in thinner steel plate (<20 mm thick) because of their smaller size and favourable bead shape (contour and penetration) than the weld beads produced at 1.0 m/min (Figure 2(a-d)). Moreover, the weld bead produced at a CTWD of 30 mm at 1.5 m/min (Figure 2 (g)) was considered most suitable due to the resultant bead shape, absence of undercut and a cross-section exhibiting a weld bead macrostructure with no pronounced centre-line. Corresponding plots of mean current, mean voltage and arc-energy heat input versus CTWD for tests 1–8 (Table 3) are shown in Figures 3-5. From these plots it is evident that a reduction in welding current (Figure 3) and an increase in voltage (Figure 4) for the trailing and leading wire result from an increase in CTWD. The net effect of this decrease in current and increase in voltage (as CTWD is increased) is a slight decrease in arc-energy heat input (Figure 5).

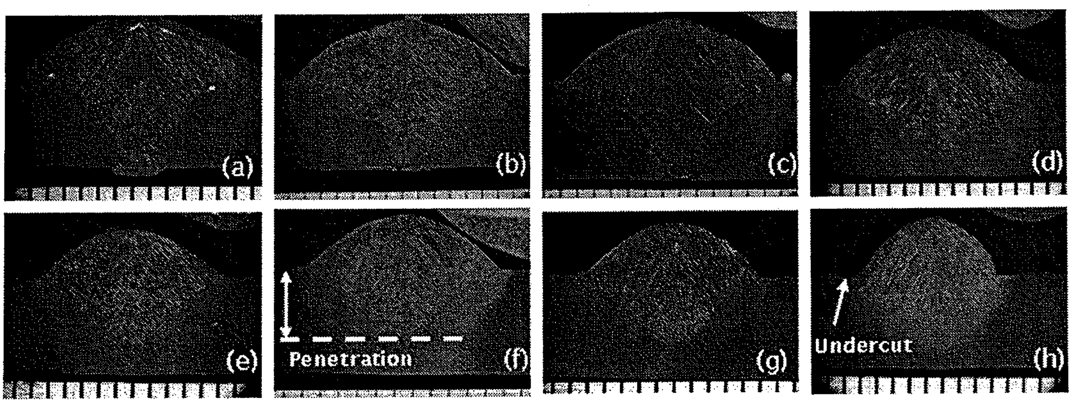

Figure 2: Photographs of the welded cross-sections for BOP tests 1–8 in Table 3: (a) test 1; (b) test 2; (c) test 3 (d) test 4 (e) test 5; (f) test 6; (g) test 7; and (h) test. Etched in 2% Nital / scales are in mm.

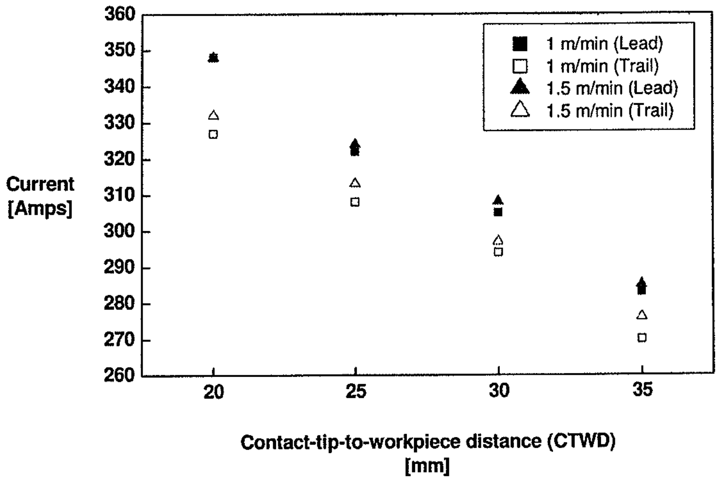

Figure 3: Mean current versus CTWD for the lead and trail electrodes at various welding travel speeds on 6 mm plain carbon steel plate.

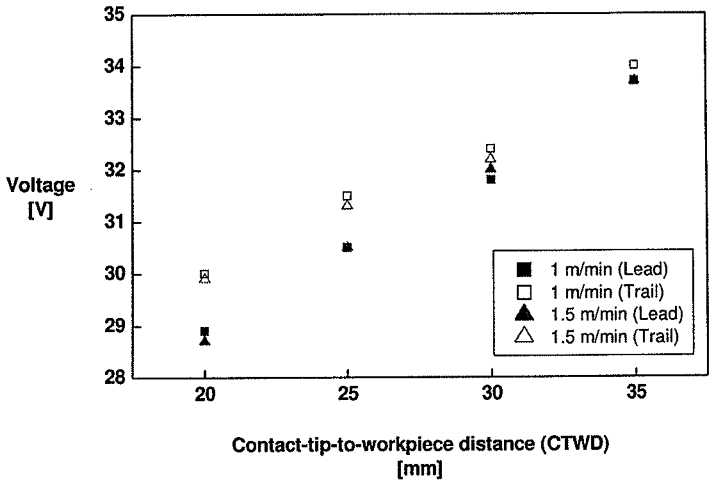

Figure 4: Mean voltage versus CTWD for the lead and trail electrodes at various welding travel speeds on 6 mm plain carbon steel plate.

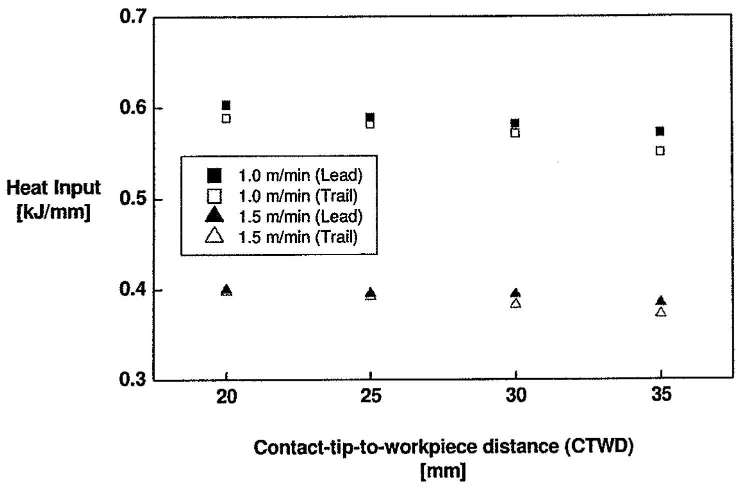

Figure 5: Arc energy heat input versus CTWD for the lead and trail electrodes at various welding travel speeds on 6 mm plain carbon steel plate.

Typical bead surfaces of the BOP weld tests undertaken on 6 mm and 20 mm plain carbon steel plate are shown in Figures 6-7, respectively. The photograph of the surface of BOP weld on the 6 mm test plate (Figure 6) shows that the leading and trailing wire cannot be distinguished, thus indicating sufficient level of weld pool mixing/interaction. However, it is evident that on the 20 mm plate, the weld bead from the trailing wire can be clearly distinguished from the weld bead of leading wire (Figure 7), thus indicating a comparatively lower level of weld pool mixing. Furthermore, the porosity that is evident near the top of the bead from test 12 (shown in Figure 8) lends support to less weld pool mixing during the BOP welding of the 20 mm steel plate compared with the 6 mm steel plate.

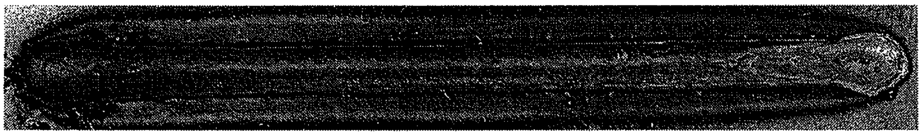

Figure 6: Photograph of the weld bead surface from BOP test 7 (6 mm plate, 30 mm CTWD and 1.5 m/min WTS) showing that the weld from the trailing electrode and the leading electrode can not be distinguished on the bead surface. This surface appearance is typical of all tests undertaken on 6 mm plate.

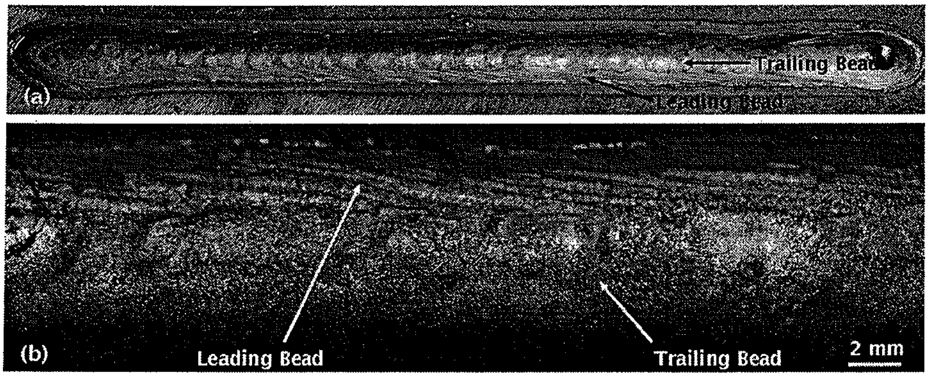

Figure 7: Photographs of weld bead surfaces from 20 mm BOP tests produced in (a) test 12 (12 m/min WFR_{lead} and 10 m/min WFR_{trail}) and (b) test 11 (14 m/min WFR_{lead} and 14 m/min WFR_{trail}) in Table 3. The weld from the trailing electrode and the leading electrode can be distinguished on the bead surface. This type of surface appearance is representative of all tests undertaken on the 20 mm plate.

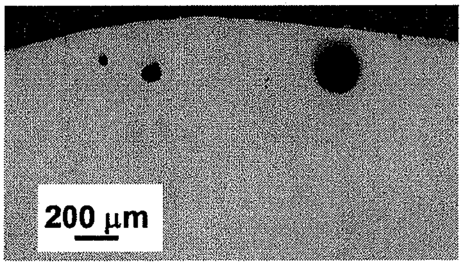

Figure 8: Low magnification photograph of part of the cross-section of the weld bead produced in test 12 (20 mm plate) showing porosity near the top of the weld (unetched). This porosity is attributed to poor/limited weld pool mixing due to the faster cooling rates experienced by the welding on 20 mm plate.

The differences observed on the weld bead surface between the 20 mm and 6 mm plate led to an investigation into the microstructure of all the tandem GMA weld beads produced. The purpose of this investigation was to determine whether weld bead solidified from a single weld pool and whether the weld metal microstructure met expected levels of homogeneity. For weld beads produced on 6 mm and 20 mm plain carbon steel plate, the weld metal microstructure of each bead showed a single solidified pool with a relatively homogenous microstructure (near the maximum resolution of optical microscopy), irrespective of whether the leading and trailing weld bead could be distinguished at the weld surface (Figures 9 and 10).

Finally, an integral part of the study was to determine the maximum WTS of the pulsed T-GMAW process. For the weld parameters used, the results show that the maximum WTS that could be achieved without compromising weld quality was 1.5 m/min (Figure 6). Irregular weld beads with significant undercut defects occurred at welding travel speeds of 1.6 and 2.0 m/min (Figure 11).

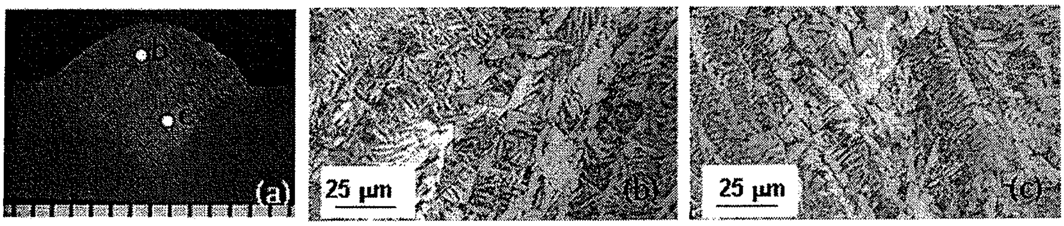

Figure 9: (a) Low magnification image of the cross-section of the weld bead produced in test 7 ((g) in Figure 2, 6 mm plate), showing the locations of the optical micrographs shown in (b) and (c). Etched in 2 % Nital.

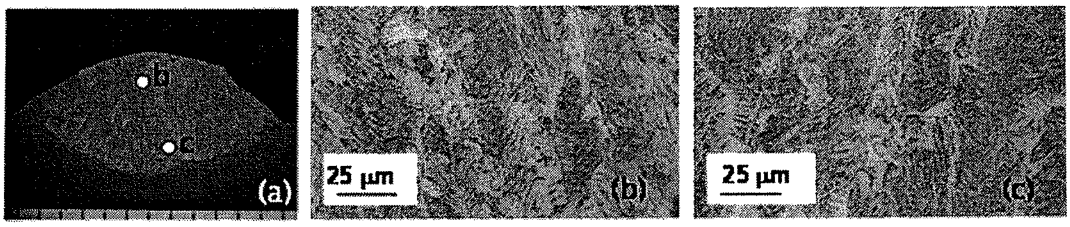

Figure 10: (a) Low magnification image of the cross-section of the weld bead produced in test 12 (20 mm plate), showing the locations of the optical micrographs shown in (b) and (c). Etched in 2 % Nital.

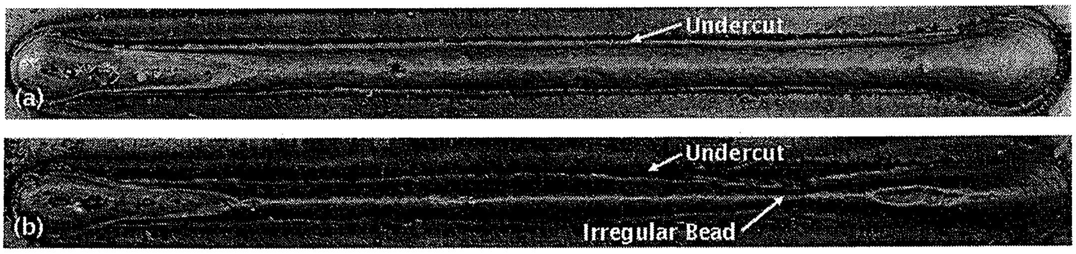

Figure 11: Photographs of the weld bead surfaces from (a) test 9 (6 mm plate, 25 mm CTWD and 1.6 m/min WTS) and (b) test 10 (6 mm plate, 25 mm CTWD and 2 m/min WTS), showing undercut and an irregular weld bead along the length of the 200 mm welds.

4. Discussion

This paper provides valuable insight into pulse T-GMAW, which is currently being evaluated as a candidate process for naval surface ship fabrication to address issues such as achieving higher productivity rates and reducing hull distortion. These issues need to be addressed by the naval shipbuilding industry in Australia in order for it to remain globally competitive and secure its long term future. Results are presented from an initial study that was focussed on developing a fundamental understanding of the sensitivity of process parameters for the pulsed T-GMAW process. The 'simple' aims of the study were to achieve process optimisation and establish a reliable operating window with respect to key variables such as WTS and CTWD. The impact of WTS and CTWD on process stability, bead profile and the level of weld metal microstructural homogeneity on BOP (6 mm plate) welds are therefore discussed. The effect of plate thickness (or weldment cooling rate) on weld quality is also addressed.

Effect of Welding Travel Speed

Significant gains in welding travel speeds are required if productivity is to be improved in naval shipbuilding yards in Australia. A well-defined window of welding parameters that can achieve faster welding travel speeds (and low distortion) without compromising weld quality is important for the wide-spread acceptance of the pulsed T-GMAW process. WTS (m/min) is typically set to accommodate the wire-feed rate setting, and a common recommendation for calculating the required WTS in GMAW processes is to use Equation 1 [8].

$$V = \frac{v \times f}{F} \qquad \textbf{(Eq. 1)}$$

: Where V = welding travel speed (m/min); v = wire-feed rate (m/min); f = cross-sectional area of the electrode (mm^2); and F = cross-sectional area of the deposited weld (mm^2).

According to Equation 1, the recommended weld-travel speed is 2.5 m/min based on a cross-sectional weld bead area of 25 mm^2 and a wire-feed rate (WFR) of 14 m/min for each electrode (as listed in Table 3). However, the results of this investigation show that a stable weld process and satisfactory weld beads could not be achieved at welding travel speeds greater than 1.5 m/min (compare Figure 6 (1.5 m/min) to Figure 11 (1.6 and 2.0 m/min)). An inspection of the welding process at travel speeds of 1.6 m/min and 2.0 m/min revealed that the process was unstable (e.g., fluctuating sound levels and arc-lengths were experienced during welding). Yudodibroto *et al* [4] lend support to these observations by reporting that there is an increased tendency for undercut and humping (excessive convexity) in T-GMAW as the WTS is increased.

Although the current literature [4, 6, 9-10] provides details for welding conditions that produce satisfactory weld beads at particular welding travel speeds, the influence of variable process parameters and their interrelationship on achieving satisfactory welds at fast travel speeds is unclear and requires a better understanding. This lack of clarity is due to (i) at least three different types/modes of T-GMAW processes covered in the literature, (ii) the high number of variable process parameters, and (iii) the complex interactions between these parameters.

Ueyama *et al* [10] report that they can consistently achieve acceptable welds at a WTS of 2.5 m/min at the same weld current ratios used in this study (0.8–1.0). However, as already mentioned, the results from the current work did not produce sound welds and a stable welding process at travel speeds greater than 1.5 m/min. This discrepancy is attributed to the key differences between the studies, which includes significantly lower values of mean current and voltage (80–240 A and 19–26 V) for the trailing electrode used by Ueyama *et al* [10] compared with those in the present study (257–332 A and 24–34 V). The work undertaken by Ueyama *et al* [10] also utilised an arc spacing of 9 mm (at a 20 mm CTWD) between the leading and trailing electrode. The implications of this are discussed in the next section, "Effect of CTWD".

From the welding experiments undertaken on 6 mm plain carbon steel plate, it is evident that acceptable weld bead profiles can be achieved at speeds of 1.0 and 1.5 m/min. For naval hull fabrication, the conditions used in test 7 (1.5 m/min WTS and 30 mm CTWD) appear to be the most suitable for achieving multiple-run welds at faster travel speeds. The wire-feed rates used in test 7 could possibly be reduced even further (resulting in a reduction in welding current) to ensure an adequate number of weld runs are achieved to meet the required levels of weldment toughness and strength. Future work will focus on increasing the WTS, and optimising wire-feed rates in order to reduce bead size and ensure process stability.

Optical microscopy of the cross-sections of all 6 mm BOP welds at 1.0 m/min and 1.5 m/min (Table 3 and Figure 2) revealed a single solidified weld bead with a relatively homogeneous microstructure (Figure 9). This level of microstructural homogeneity is typical of that seen in weld beads produced by conventional single-wire GMAW and the weld beads produced in tests 1–8 (Figure 2). The weld metal deposited by the trailing wire and leading wire could not be distinguished on the weld surface in tests 1-8 (Table 3), which suggests that adequate weld pool mixing occurs in the welding of 6 mm plate (Figure 6).

Effect of CTWD

Contact-tip-to-workpiece distance (defined in Figure 1(b)) is an important parameter in pulsed T-GMAW processes. There are both productivity and metallurgical benefits to be gained in using a relatively higher CTWD. The reduction in welding current that results from an increase in CTWD (Figure 3) enables the implementation of higher wire feed rates to improve productivity. This is important for high deposition rate welding processes, particularly if the current capacity of the welding machines is limited. An increase in CTWD can also increase welding voltage (Figure 4) and reduce susceptibility to weld defects such as hydrogen assisted cold cracking (HACC), due to the resulting increase in the size of the electrical-resistive-heating zone. The net effect of this trend, combined with the drop in current shown in Figure 3, is a slight decrease on arc-energy heat-input for each individual electrode (Figure 5). If there is no reason for concern with respect to HACC susceptibility, the increase in voltage that results from an increase in CTWD could be negated through the manipulation of arc-length [11], which is an available option with the equipment used. For all CTWD values investigated on the 6 mm plate (at 1.0 and 1.5 m/min), adequate weld pool mixing occurs. This is evidenced by the surface profiles of the weld beads (Figure 6), the absence of porosity, and the presence of weld bead that has solidified from a single weld pool (Figure 9).

The considerations for CTWD are more complicated in T-GMAW compared with single wire GMAW (pulsed or standard) because of the interaction that can occur between the arcs of the two wires. Increasing CTWD decreases the distance between the two arcs in a fixed head arrangement (as can be seen in Figure 1(b)), thus increasing the likelihood of adverse arc interaction. Inspection of the pulsed

T-GMAW process revealed that when the leading and trailing arcs were too close together, unwanted metal transfer occurred between them above the arc in the electrical-resistive-heating zone (as was observed in tests 4 and 8 (35 mm CTWD at 1.0 and 1.5 m/min, respectively)). Separate control of CTWD and arc distance (between the leading and trail wires) may lead to less stringent control requirements of other weld parameters. The current authors are not aware of the commercial availability of such an arrangement for the equipment used in this work.

Ueyama *et al* [10] have developed a plot which shows combinations of WTS and current ratio (of the trailing and leading wire) that produce both acceptable and poor quality weld beads at a CTWD of 20 mm (Figure 13). Interestingly, all welds from the current test program fall into the acceptable weld region when overlayed onto the plot by Ueyama *et al* (Figure 13). However, there were three test conditions in the current study that led to unacceptable welds. Two of them were due to excessive welding travel speeds for the parameters used (as discussed previously in "Effect of Welding Travel Speed"). The other test condition that resulted in an irregular (excessively convex) weld bead with pronounced undercut was at a CTWD of 35 mm and a WTS of 1.5 m/min (Figure 2(h)). This result suggests that achieving acceptable weld bead quality at higher travel speeds can be sensitive to CTWD.

The underlying barrier to producing a quality weld at a CTWD of 35 mm at 1.5 m/min could be the small set-distance between the two arcs. This view is supported by the work of Hedegard *et al* [6], who report that small electrode spacing systems (such as those at a high CTWD in pulsed T-GMAW) exhibit bulging of the molten weld pool, which in turn adversely affects the stability of the welding process. Additionally, the slightly higher mean weld current ratio (0.968) at a CTWD of 35 mm and 1.5 m/min compared with the mean weld current ratio (0.954) at a CTWD of 35 mm and 1.0 m/min may also contribute to the formation of an irregular weld bead since the flow velocity of the molten weld pool behind the trailing arc will increase slightly [10], thus promoting irregular bead formation. Therefore, any future models that predict weld bead quality should attempt to incorporate CTWD, as well as arc spacing and higher welding currents for the trailing electrode, to provide a reliable set of welding parameters that will produce quality welds at high travel speeds.

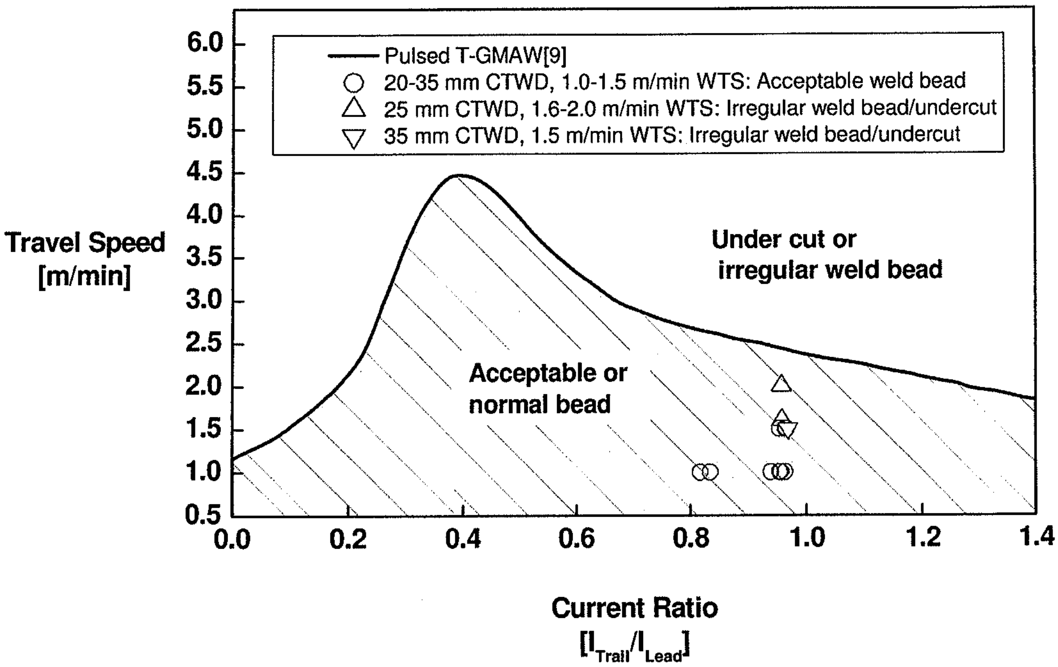

Figure 13: A plot of welding travel speed versus current ratio of the trailing and leading wire in pulsed T-GMAW showing the resulting weld quality for given combinations [10]. Data from the current tests (listed in Table 3), which are overlayed onto the plot, confirm that weld bead quality is less likely at higher welding travel speeds and that it is also sensitive to CTWD.

Effect of Plate Thickness

Naval surface ship plate thicknesses can typically vary from 6 mm to over 20 mm. Under the same set of welding parameters, greater plate thicknesses produce faster weldment cooling rates, and this can limit the time available for adequate weld pool interaction or mixing. The composition of the weld pool tends to be homogenised by fluid motion—the importance of this is mostly reported in regard to the welding of austenitic stainless steels [12]. Similarly, T-GMAW is a process where adequate weld pool mixing is important, particularly since very fast welding travel speeds may only be achieved at current ratios (between the trailing and leading wire) of 0.3–0.6 [10].

BOP tests completed on 20 mm plain carbon steel plate revealed a limitation in the amount of weld pool mixing that occurs (Figure 7). This limitation can be attributed to the faster cooling rates experienced in thicker plate, evidenced by the fine microstructure in the weld bead (Figure 10) and narrow HAZ width (Figure 6) in the 20 mm steel plate compared with relatively coarse microstructure (Figure 9) and wider HAZ (Figure 7(a)) in the 6 mm steel plate. Adequate weld pool mixing is essential for achieving satisfactory compositional homogeneity [12], acceptable microstructural homogeneity and uniform properties across the weld bead. The release of welding gases into the atmosphere can also be hindered by limited time for adequate weld pool mixing, as shown by the presence of gas porosity at the top of the weld bead in the T-GMAW of 20 mm plate (Figure 8). An increase in pre-heat treatment temperature would negate the economic advantages of T-GMAW, and may not eliminate the surface effect created by limited weld pool mixing since a 10 mm wide HAZ is not as common in thicker steel plates as it is in thin steel plate. Nonetheless, suitable preheat treatment temperature might allow time for welding gases to escape the molten weld pool. Hedegard *et al* [6] proposes that larger arc-separation may possibly promote further weld pool stirring due to the additional weld pool effect that could be created by a longer weld pool. However, the independent control of arc-separation and CTWD is not commercially available for the pulsed T-GMAW equipment that was used.

5. Conclusions

The following conclusions can be drawn from the experimental conditions used in the current work.

1. Pulsed T-GMAW has great potential for the weld fabrication of naval surface ships.
2. Adequate weld pool mixing and a weld bead produced from a single weld pool (with an acceptable level of homogeneity in the weld metal microstructure) was achieved for all welding undertaken on 6 mm plain carbon steel plate.
3. A weld bead produced from a single weld pool (with an acceptable level of homogeneity in the weld metal microstructure) was achieved in all welding undertaken on the 20 mm BOP tests, but there was evidence of limited weld pool mixing.

4. The maximum WTS that could be achieved whilst maintaining an acceptable weld bead was 1.5 m/min.
5. Weld process stability and weld quality is sensitive to WTS and CTWD, possibly by virtue of the fact it influences arc spacing or the flow velocity of the molten weld pool.

Future work will focus on increasing the WTS, and optimising wire-feed rates for both the leading and trailing wire in order to reduce bead size and ensure process stability.

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